TECHNISCHE UNIVERSITÄT DARMSTADT

Institut für Elektrische Energiewandlung

Energy Converters

Guide for Computer Aided Design

- Asynchronous Machine -

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This guide is to facilitate the design of the asynchronous machine with the program PC-IMD. The design of the machine model from the lecture script “Energy Converters - CAD and System Dynamics” is presented. The input data, needed by the program, are bold printed indicated in the appropriate places (**variable = value**).
In the program PC-IMD there are two important editors, where data have to be specified for the machine calculation. One of them is the **template editor**, where part of the geometric dimensions of the machine, calculation methods and further boundary conditions are chosen. The other one is the **outline editor**, where detailed geometric dimensions of stator, rotor and shaft are specified and also visualized with different view options. In the following the values that have to be specified in the **template editor** are printed as (**TE: variable=value**), while the values that have to be specified in the **outline editor** are printed as (**OE: variable=value**). **Fig. 0** shows where to select the different editors.

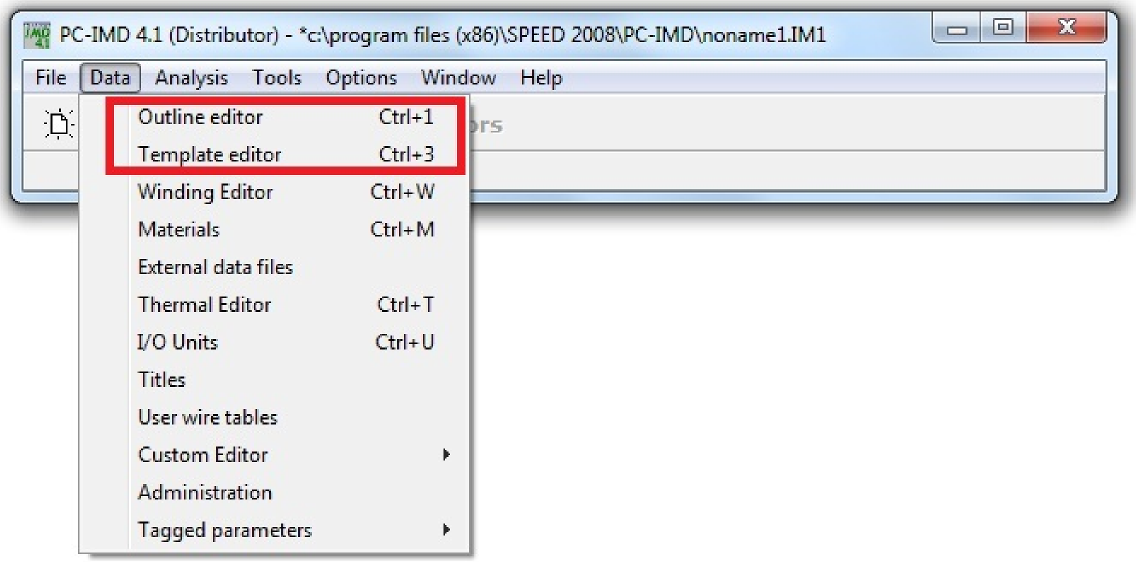


Fig. 0: Screenshot PC-IMD menu bar – editor selection

Machine design:

Given data:

Asynchronous motor with squirrel-cage rotor (C-rotor)				(**TE: Bar1 = Type2**)
Rated power:	P_N	=	500 kW	(**TE: PowrSh. = 500 000.0**)
Rated voltage:	U_N	=	6 kV	(**TE: Vs = 6000.0**)
Rated frequency:	f_N	=	50 Hz	(**TE: Freq = 50.0**)
Number of poles:	$2p$	=	4	(**TE: Poles = 4**)

As the frequency and the power at shaft is given we choose the calculation method (**TE: CalcMode=f/PowerSh**) and (**TE: TorqCalc = LR + Brk + NL**) in the template editor.

Aim is to design a machine with efficiency and a power factor as high as possible. By the design some conditions are to be kept:

- Overload capability: $3 > M_b/M_N > 1.6$

- Starting current: $4 < I_1/I_N < 6$

- Starting torque: $0{,}7 < M_1/M_N < 1.6$ (i.e. starting torque should not be too small, however not unnecessarily high)

- Winding temperature rise: ISO-Kl. B

1. Calculation of main design geometry data

1.1. Electromagnetic and thermal utilization

A time-dependent temperature rise calculation is not carried out (**TE: TempCalc = fixed**). The ambient temperature is 20 °C (**TE: Ambient = 20.0**), stator and rotor temperature according to ISO-Kl. B 75 °C (**TE: WdgTemp = 75.0**; **TE: RoTemp = 75.0**). At the beginning of the design several parameters have to be estimated, respectively initial values for these parameters must be chosen, which could change during the design process. For simplification, given curves of optimised machines will be used during the design. From Fig. 2.1-3 to Fig. 2.1-10 (see [1]) the following initial values are extracted:

Table 1: Initial values of the design

Notation	Value	To insert as
Number of poles	$2p = 4$	**TE: Poles = 4**
Efficiency	$\eta_N = 0{,}94$	
Power factor	$\cos\varphi_N = 0{,}868$	
Pole pitch	$\tau_p = 36$ cm	
Equivalent iron stack length	$l_e = 38$ cm	
Current loading	$A_s = 485$ A/cm	
Air gap flux density	$B_{\delta,av} = 0{,}56$ T ... 0,63 T	
Current density	$J_s = 5{,}5$ A / mm^2	
Air gap width	$\delta = 0{,}14$ cm	**OE: Gap = 1.4 mm**
Inner rotor diameter and shaft radius	$d_{ri} = 20$ cm $r_{shaft} \cong r_{ri} = \frac{d_{ri}}{2}$	**OE: RadSh = 100 mm**

From the initial values (Table 1) we find:

- Apparent power:

$$S_N = \frac{P_N}{\eta_N \cdot \cos\varphi_N} = \frac{500 \cdot 10^3}{0.944 \cdot 0.868} \cong 610\,\text{kVA}$$

- Motor current:

$$I_N = \frac{S_N}{\sqrt{3} \cdot U_{sN}} = \frac{610 \cdot 10^3}{\sqrt{3} \cdot 6 \cdot 10^3} \cong 59\,\text{A}$$

- Synchronous speed:

$$n_{syn} = f_s / p = 1500\,/\text{min}$$

- Stator bore diameter:

$$d_{si} = 2p\tau_p / \pi = 458\,\text{mm}.$$

Stator inner radius: $r_{si} = d_{si}/2 = 229\,\text{mm}.$

Rotor outer radius: $r_{ro} = d_{si}/2 - \delta = 227.6\,\text{mm}$ **(OE: Rad1= 227.6 mm)**

- Internal apparent power for the stator stray coefficient $\sigma_s = 0.08/2 = 0.04$:

$$S_\delta = S/(1+\sigma_s) = 610 \cdot 10^3 / 1.04 = 587\,\text{kVA}$$

- Electromagnetic utilization: $C = S_\delta /(d_{si}^2 \cdot l_{Fe} \cdot n_{syn}) = \dfrac{587 \cdot 10^3}{0.458^2 \cdot 0.38 \cdot 1500} = 4.89\,\text{kVA·min/m}^3$

With the stator stray coefficient $\sigma_s = 0{,}04$ and winding factor $k_{ws} = 0{,}91$ estimated as initial values, the air gap flux density results:

$$C = \frac{\pi^2}{\sqrt{2}} \cdot k_{w1} \cdot A \cdot B_\delta \quad \Rightarrow \quad B_\delta = \frac{\sqrt{2} \cdot C}{k_{w1} \cdot A \cdot \pi^2} = \frac{\sqrt{2} \cdot 4.89 \cdot 10^3 \cdot 60}{\pi^2 \cdot 0.91 \cdot 500 \cdot 100} = 0.954\,\text{T}.$$

and the average:

$$B_{\delta,av} = \frac{2}{\pi} \cdot B_\delta = \frac{2}{\pi} \cdot 0.954 \cong 0.6\,\text{T}$$

Machines of this power class are equipped in axial direction with round cooling ducts. The lamination stack is divided into individual packages. According to [1] we will assume that both iron stacks, stator and rotor, consist of 9 sections with l_1 = 42 mm and 8 radial ducts (switch **OE** to axial view **OE: NSDuct = 8** and **OE: NRDuct = 8**) with width l_k = 10 mm (**OE: WSDuct = 10 mm** and **OE: WRDuct = 10 mm**). The iron stacks length results:

$$l_{Fe} = 9 \cdot l_1 = 9 \cdot 42 = 378\,\text{mm}.$$

The total axial length will be extended in this case by the width of the cooling ducts:

$$L = 9 \cdot l_1 + 8 \cdot l_k = 9 \cdot 42 + 8 \cdot 10 = 458\,\text{mm}$$ **(OE: Lstk = 458 mm)**

The length of the winding extension at each end of iron stack must be determined and inserted into the program. In dependence of the voltage (Table 2.8.3-2 [1]) the following value will be considered: l_a=5.7 cm (**TE: Ext=57.0**).

1.2. Design of the stator winding

The stator slot pitch τ_{Qs} changes with the number of coils per pole and phase q which is to be chosen. As q has an effect on the harmonic content of the winding it cannot be selected arbitrarily. The influence of q should be clarified within a table. The stator slot pitch consists of the tooth width b_{ds} and the slot width b_{Qs}. The tooth width may not be smaller than a minimum value for which the tooth flux density B_{ds} becomes inadmissibly high. The minimum tooth width $b_{ds,min}$ is determined by linear calculation, without field flattening and for an iron fill factor of $k_{Fe} = 0{,}95$ (**OE: Stf = 0.95**).

$$b_{ds,\,min} = \frac{B_{\delta,av} \frac{\pi}{2}}{B_{ds,\,max}} \frac{\tau_{Qs}\left(1+\sigma_s\right)}{k_{Fe}}$$

The maximum tooth flux density is assumed to 2.4 T (higher value because it is calculated without flattening). Thus the maximal permissible slot width can be indicated and the distribution and pitching factors can be calculated (see Table 2) with expressions:

$$k_{d\nu} = \frac{\sin\left(\frac{\nu\pi}{2m_s}\right)}{q\sin\left(\frac{\nu\pi}{2m_s q}\right)}\ ; \quad k_{p\nu} = \sin\left(\nu\frac{m_s q - s}{m_s q}\frac{\pi}{2}\right) = \sin\left(\nu\frac{W}{\tau_p}\frac{\pi}{2}\right)$$

Table 2: Choice of number of coils per pole and phase and short-pitching of the stator winding

					To insert as
Number of slots per pole and phase q:	3	4	***5***	6	**TE: CPP = 5**
Number of stator slots $Q_s = 2\,p\,m_s\,q$:	36	48	***60***	72	**TE: Slots = 60**
Slot pitch $\tau_{Qs} = \tau_p / (m_s\,q)$ in cm:	4,00	3,00	***2,40***	2,00	
Tooth width b_{dsmin} in cm:	1.17	1,31	***1,04***	0,87	
Slot width $b_{Qs} = \tau_s - b_{dsmin}$ in cm:	2.26	1,17	***1,36***	1,13	
Ratio b_{Qs} / τ_{Qs}:	0,56	0,56	***0,56***	0,56	
Pole pitch in slots τ_p:	9	12	15	18	
Distribution factor k_{d1} :	0,9598	0,9577	0,9567	0,9561	
Distribution factor k_{d5} :	0,2176	0,2053	0,2000	0,1972	
Distribution factor k_{d7} :	-0,1774	-0,1576	-0,1494	-0,1453	
Coil pitching with 1 Slot (s = 1):	8	11	14	17	
Pitching factor k_{p1} :	0,9848	0,9914	0,9945	0,9962	
Winding factor k_{w1} :	0,9452	0,9495	0,9514	0,9525	
Pitching factor k_{p5} :	0,6428	0,7934	0,8660	0,9063	
Winding factor k_{w5} :	0,1398	0,1629	0,1732	0,1787	
Pitching factor k_{p7} :	-0,3420	-0,6088	-0,7431	-0,8192	
Winding factor k_{w7} :	0,0607	0,0959	0,1111	0,1190	
Coil pitching with 2 Slots (s = 2):	7	10	13	16	
Pitching factor k_{p1} :	0,9397	0,9659	0,9781	0,9848	
Winding factor k_{w1} :	0,9019	0,9250	0,9358	0,9416	
Pitching factor k_{p5} :	-0,1736	0,2588	0,5000	0,6428	
Winding factor k_{w5} :	-0,0378	0,0531	0,1000	0,1267	
Pitching factor k_{p7} :	0,7660	0,2588	-0,1045	-0,3420	
Winding factor k_{w7} :	-0,1359	-0,0408	0,0156	0,0497	
Coil pitching with 3 Slots (s = 3):	6	9	***12***	15	**TE: Throw = 12**
Pitching factor k_{p1} :	0,8660	0,9239	***0,9511***	0,9659	
Winding factor k_{w1} :	0,8312	0,8848	***0,9099***	0,9236	
Pitching factor k_{p5} :	-0,8660	-0,3827	***0,0000***	0,2588	
Winding factor k_{w5} :	-0,1884	-0,0786	***0,0000***	0,0510	
Pitching factor k_{p7} :	0,8660	0,9239	***0,5878***	0,2588	
Winding factor k_{w7}:	-0,1536	-0,1456	***-0,0878***	-0,0376	

With the choice of q, we are trying to reduce the fifth harmonic wave amplitude of mmf. at an as small as possible value. From Table 2, it becomes evident that both $q = 4$ and $q = 5$ provide reasonable results and fulfil the conditions (see [1]): b_{Qs}/τ_{Qs} = 0.5 ... 0.6 and 1 cm < b_{Qs} < 2 cm. Here $q = 5$ is selected with a short-pitching of $s = 3$. The winding diagram created by SPEED is presented in Fig.1 for the chosen case: q = 5 and $\frac{W}{\tau_p} = \frac{12}{15}$.

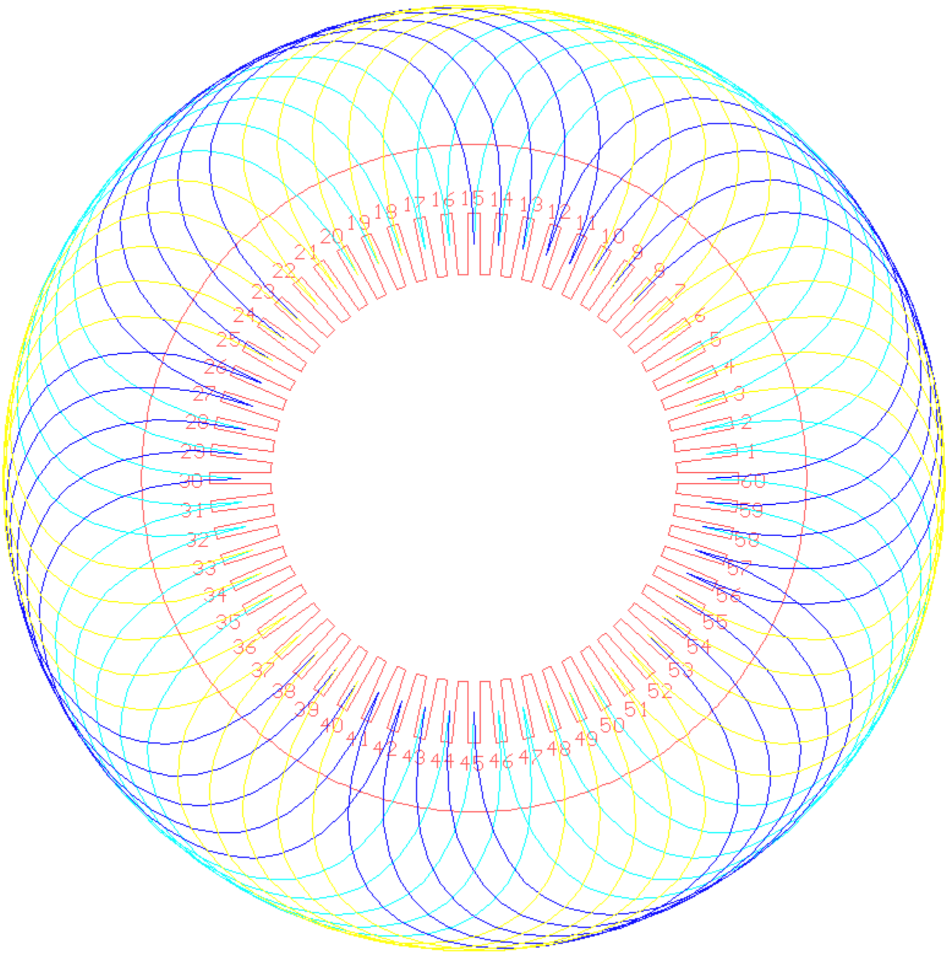


Fig. 1: Winding diagram created by SPEED (WdgType = Lap)

1.3. Choice of number of turns

The considered winding is a three-phase, double-layer winding in y-connection (**TE : Connex = 3-PhWye; TE: WdgType = Lap ; TE: CoilForm = None**).

The number of turns per phase is calculated as:

$$N_s = \frac{U_h}{\sqrt{2}\pi f_s \cdot k_{w1} \cdot \Phi_h} = \frac{3330}{\sqrt{2}\pi \cdot 50 \cdot 0.91 \cdot 83.12 \cdot 10^{-3}} \cong 198 \text{ turns /phase}$$

where the estimated induced voltage per phase is:

$$U_h = \frac{U_N / \sqrt{3}}{1 + \sigma_s} = \frac{6000 / \sqrt{3}}{1.04} = 3330\,\text{V}$$

and the main flux per pole of fundamental $\nu = 1$ is for the air gap flux density $B_{\delta,\nu=1} = 0.954\,\text{T}$:

$$\Phi_h = \frac{2}{\pi} \cdot \tau_p \cdot l_e \cdot B_{\delta,\nu=1} = \frac{2}{\pi} \cdot 0.36 \cdot 0.38 \cdot 0.954 = 83.12\,\text{mWb.}$$

By a roughly assumption we have considered, for a preliminary estimation, the stator iron length equal to the equivalent iron length: $l_{\mathrm{Fe}} \approx l_{\mathrm{e}} \cong 380\,\mathrm{mm}$.

The number of turns per coil is:

$N_{\mathrm{c}} = N_{\mathrm{s}} \cdot a/(2pq) = 198 \cdot 1/(2 \cdot 2 \cdot 5) = 9.9$, so the integer value $N_{\mathrm{c}} = \underline{\underline{10}}$ (**TE: TC = 10)** for a = 1 (**TE: Ppaths = 1**) is chosen.

The values for the number of turns per phase, flux, flux density and current loading are to be determined thereby again:

Table 3: Corrected values

Number of turns per phase	$N_{\mathrm{s}} = 2pqN_{\mathrm{c}} = 200$
Flux density	$B_{\delta} = 0{,}946\,\mathrm{T}$
Air gap flux	$\hat{\Phi}_{\mathrm{h}} = 82.4\,\mathrm{mWb}$
Current loading	$A = \dfrac{2m_{\mathrm{s}}N_{\mathrm{s}}I_{\mathrm{s}}}{2p\tau_{\mathrm{p}}} = 491\mathrm{A/cm}$

The thermal utilization is $A \cdot J = 491 \cdot 5.5 = 2700.5\,(\mathrm{A/cm}) \cdot (\mathrm{A \cdot mm^2})$ which is a permissible value for a 500 kW induction machine (see [1]).

Obs:

Since the terminal voltage is an effective constant value, the air gap flux density depends on the number of turns per phase. If the air gap flux density is selected too small, the machine is poorly used and a larger number of turns per phase will be necessary in order to come to the given voltage. Possibly the necessary place is not available in the slot for this number of turns. If the flux density is selected too big, the iron will be strongly saturated and the magnetisation demand becomes too high!

1.4. Slot dimensions

The designed winding is a high-voltage winding. The slot flanks are parallel. The coils are inserted into the slot and then the conductor width must correspond to the slot opening. Because profile copper is used, rectangular conductors are specified in the winding parameters (**TE: Wire_1=Rect**). As can be seen from Table 2, for q = 5, the maximal permissible slot width is $b_{Q\mathrm{s}}$ = 1.36 cm and the minimal calculate permissible slot is $b_{Q\mathrm{s}}$ = 1.04 cm. The slot width is fixed here to $b_{Q\mathrm{s}}$ = 1,25 cm and from this, further conductor dimensions and slot dimensions (Table 4 and Table 6) are determined according to the text script [1]. The initial value for the outer radius of the stator is with 50 mm much smaller than the already chosen radius of the rotor. In order to have a better overview of the change of the stator slots we set the outer radius of the stator arbitrarily to 400 mm (**OE: Rad3 = 400**). The final value of the stator outer radius will be later calculated.

Table 4: Conductor and slot width dimensions

Slot geometry	Parallel flanks		**OE: S-Slots = PllSlot**
Slot width b_{Qs}:	12.5 mm		**OE: SWid = 12.5**
Conductor insulation d_{ic}:	0.40 mm		
Slot-lining:	0.15 mm	One-side	**TE: Liner = 0.15**
Main insulation:	2.2 mm	One-side	
Tolerance (slot play) b_{Tol}:	0.3 mm		
Insulation width b_{Is}:	4.7 mm	2times slot-lining + 2times main ins.	
Conductor width b_{L}	7.1 mm	$b_{\mathrm{L}} = b_{Q\mathrm{s}} - b_{\mathrm{Is}} - b_{\mathrm{Tol}}$	**TE: wa_1**

=7.1

Conductor cross section is checked: $A_{\mathrm{TL}} = I_{\mathrm{s}}/(J_{\mathrm{s}} \cdot a \cdot a_i) = 59/(5.5 \cdot 1 \cdot 1) = 10.73$ mm^2 and for $b_{\mathrm{L}} = 7.1$ mm and for the smallest admissible area of the conductor $A_{\mathrm{TL}} = 12.42$ mm^2 (see Table 5) the conductor height $h_{\mathrm{L}} = 1.8$ mm is chosen.

Table 5: Selection of available profile copper wire: dimensions without enamel coating and cross section (edges of wire rounded by 0.5 mm .... 1.0 mm radius)

b_{L} (mm)	Conductor height h_{L} (mm)									
	1.8	*2*	*2.24*	*2.5*	*2.8*	*3.15*	*3.55*	*4*	*4.5*	*5*
5	8.637	9.637	10.84	11.95	13.45	15.20	17.22	-	-	-
5.6	9.717	10.84	12.18	13.45	15.13	17.09	19.33	21.54	-	-
6.3	10.98	12.24	13.75	15.20	17.09	19.30	21.82	24.34	27.49	-
7.1	12.42	13.84	15.54	17.20	19.33	21.82	24.66	27.54	31.09	34.64
8	14.04	15.64	17.56	19.45	21.85	24.65	27.85	31.14	35.14	39.14
9	15.84	17.64	19.80	21.95	24.65	27.80	31.40	35.14	39.64	44.14
10	17.64	19.64	22.04	24.45	27.45	30.95	34.95	39.14	44.14	49.14
11.2	19.80	22.04	24.73	27.45	30.81	34.73	39.21	43.94	49.54	55.14
12.5	22.14	24.64	27.64	30.70	34.45	38.83	43.83	49.14	55.39	61.64
14	24.84	27.64	31.00	34.45	38.65	43.55	49.15	55.14	62.14	69.14
16	-	31.64	35.48	39.45	44.25	49.85	56.25	63.14	71.14	79.14

The wire insulation thickness is set to 0.15 mm **(TE: InsThk1 = 0.150)**.

Table 6: Conductor and slot height dimensions

Cond. height h_{L}:	1,80 mm	**TE: wb_1=1.80**
Inter-turn insulation:	0.3 mm	
Conductor insulation d_{ic}:	0.4 mm	
Coated coil:	24.7 mm	$N_{\mathrm{c}} \cdot (h_{\mathrm{L}} + d_{\mathrm{ic}}) + (N_{\mathrm{c}}-1) \cdot$inter-turn ins.
Main insulation	4.4 mm	
Insulated coil upper layer:	29.1 mm	
Two coils per slot	58.2 mm	
Inter-layer insulation:	4,0 mm	
Slot-lining (3 times):	0,45 mm	
Wedge:	4,5 mm	
Top and Bottom lining:	0.8 mm	
Vertical play:	1.05 mm	
Slot height h_{Qs}:	69,0 mm	**TE: SD_S = 69.0**
Stator tang depth $h_{4\mathrm{s}}$	0 mm	**TE: TGD_S = 0.001***

(*Speed Software cannot handle $h_{4s} = 0$, therefore a small value is inserted)

The magnetic circuit computation assumes parallel-sided stator teeth. Simplified calculation takes H_{d} on 1/3 of tooth length at the narrower side to calculate the mmf. Then:

$$\tau_{Q\mathrm{s},1/3} = (d_{\mathrm{si}} + (2/3) \cdot l_{\mathrm{ds}}) \cdot \pi / Q_{\mathrm{s}} = (458 + (2/3) \cdot 69) \cdot \pi / 60 = 26.38\,\mathrm{mm}$$

$$b_{\mathrm{ds},1/3} = \tau_{Q\mathrm{s},1/3} - b_{Q\mathrm{s}} = 26.38 - 12.5 = 13.9\,\mathrm{mm}$$

1.5. Determination of the rotor winding parameters of the squirrel-cage rotor

Choice of rotor slot number Q_r must be done with respect to stator number Q_s. (see Lectures: "Motor development for electric drive systems"). We get as choice the slot numbers from Table 7.

Table 7: Choice of rotor slot number Q_r

According to the script for and number of pole pairs the following rotor slot numbers Q_r Are permitted for unskewed rotor bars:	$Q_s = 60$ stator slots $p = 2$ 50, 54, 66, 70	 **TE: Skew = 0**
Selected number of rotor slots:	$Q_r = 50$ rotor slots	**TE: R_Bars = 50**

Rotor cage is designed according to rotor bar current:

$$I'_r = I_r / \ddot{u}_I \approx I_s \cdot \cos\varphi_s = 59 \cdot 0.868 = 51.21\,\text{A},\ \ddot{u}_I = \frac{2k_{ws}m_s N_s}{Q_r} = \frac{2\cdot 0.91\cdot 3\cdot 200}{50} = 21.84$$

$$I_r = \ddot{u}_I \cdot I'_r = 21.84 \cdot 51.33 = 1118\ \text{A}$$

The rotor bar current density results:

$$J_r = I_r / A_{Cu} = 1118/200 = 5.6\ \text{A/mm}$$

Deep bar rotor to increase starting torque should respect the ratio $h_{Cu}/b_{Cu} \geq 8$. Then: $h_{Cu} = 40$ mm and $b_{Cu} = 5$ mm with the cross section: $A_{Cu} = 200\ \text{mm}^2$.

The necessary ring cross section:

$$A_{Ring} = I_{Ring} / J_{Ring} = 4462/5.6 = 798\ \text{A/mm}^2$$

Where:

- Rotor ring current: $I_{Ring} = I_r /(2\cdot\sin(p\pi/Q_r)) = 1121/(2\cdot\sin(2\pi/50)) = \underline{\underline{4462}}\,\text{A}$
- Ring current density: $J_{Ring} = J_r = 5.6\,\text{A/mm}^2$,

Table 8. Rotor cage dimensions

<u>Conductor dimensions:</u> Winding factor k_{wr}: Choice of bar height and bar width: Bar height h_{Cu}: Bar width b_{Cu}:	 1 40 mm 5 mm	 by cage windings	 **OE: BarDpth = 40** **OE: BarWdth = 5**
Set-back h_{4r}:	3.5 mm	acc. To text script [1]	**OE: SetBack = 3.5 mm**
Rotor slot opening s_{Qr}	2.5 mm		**OE: SO_R = 2.5 mm**
<u>Ring height and axial width:</u> Ring height h_{Ring} Additional radial ring height:	 40 mm 0 mm	 Ring height is usually at least bar height: $h_{Ring} > h_{Cu}$ $h_z = h_{Ring} - h_{Cu}$	 **OE: ERLedge1 = 0** **OE: ERLedge2 = 0**

Ring width b_{Ring}:	20 mm	**OE: Erthk1 = 20** **OE: Erthk2 = 20**

The set-backs in the rotor are not filled with copper, therefore (**TE: SBFull = false**).
As copper is used as rotor bars, the cage- and end-ring density is set to the one of copper which is 8900 kg/m³ **(TE: CgDensity = 8900 kg/m³) (TE: ERDensity = 8900 kg/m³)**.

1.6. Yoke radii

The permissible flux density $B_y \leq 1{,}7 \div 1.8$ T determines the thickness of the stator and rotor back.

For stator:

$$h_{\text{ys}} = \frac{\Phi_\delta \cdot (1+\sigma_{\text{s}})/2}{l_{\text{Fe}} \cdot k_{\text{Fe}} \cdot B_{\text{ys}}} = \frac{82.4 \cdot 10^{-3} \cdot (1+0.04)/2}{0.378 \cdot 0.95 \cdot 1.8} \cong 70 \text{ mm},$$

value which can be increased according to motor performances. Let’s accept: h_{ys} = 77 mm.
Recalculate value of stator maximum flux density:

$$B_{\text{ys}} = \frac{\Phi_\delta \cdot (1+\sigma_{\text{s}})/2}{h_{\text{ys}} \cdot l_{\text{Fe}} \cdot k_{\text{Fe}}} = 1.54 \text{ T}$$

The stator outer diameter results:

$$d_{\text{so}} = d_{\text{si}} + 2l_{\text{ds}} + 2h_{\text{ys}} = 458 + 2 \cdot 69 + 2 \cdot 77 = 750 \,\text{mm}$$ **(OE: Rad3= 375 mm)**

Without flux penetration in shaft, the rotor height back is:

$$h_{\text{yr}} = \left[d_{\text{si}} - 2\delta - 2l_{\text{dr}} - d_{\text{ri}}\right]/2 = \left[458 - 2 \cdot 1.4 - 2 \cdot 43.5 - 200\right]/2 = 84.1 \,\text{mm}$$

For axial cooling four ducts with a diameter of c_2 = 30 mm it results: **(OE: NumHoles = 4)**

$$h_{\text{yr,e}} = h_{\text{yr}} - (2/3) \cdot c_2 = 84.1 - 2/3 \cdot 30 = 64.1 \,\text{mm}$$ **(OE: HoleDia=30 mm)**

The radius for the circle, on which the axial cooling ducts lie (pitch circle), is is set to 286.5 mm **(OE: PCDia = 286.5 mm)**.

Rotor maximum yoke flux density is:

$$B_{\text{yr}} = \frac{\Phi_\delta /2}{h_{\text{yr,e}} \cdot l_{\text{Fe}} \cdot k_{\text{Fe}}} = \frac{(2/\pi) \cdot B_{\delta,\nu=1} \cdot \tau_{\text{p}} \cdot l_{\text{e}}/2}{h_{\text{yr,e}} \cdot l_{\text{Fe}} \cdot k_{\text{Fe}}} = 1.85 \text{ T}$$

In the reality this value will be much smaller due to the shaft presence (see [1]) and a round cooling duct with c_2 = 30 mm may be accepted.

Now all values for the calculation of the machine with the PC-IMD program are available!
In Fig.2 the geometry of the induction machine is given, as it has been generated by SPEED, with details of the stator and rotor slots.

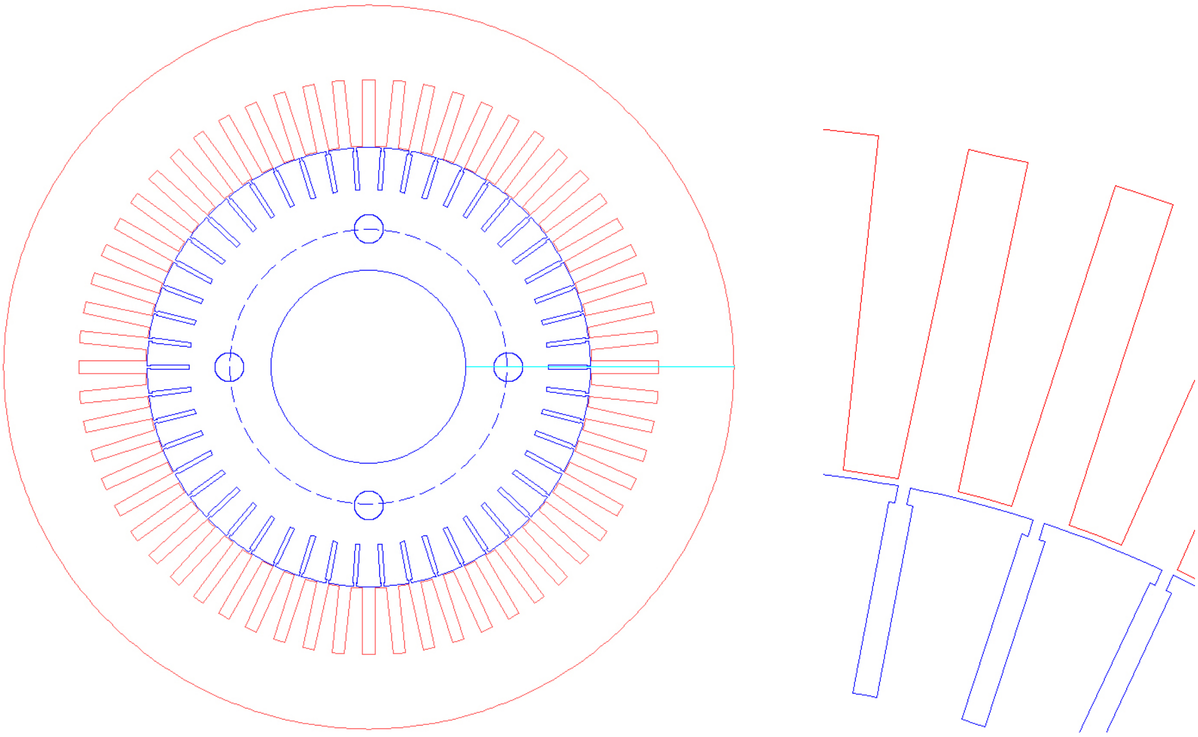


Fig. 2 Geometry of 500kW induction machine

1.7 Setting of calculation methods

Before performing the calculation several calculation method settings for simulation have to be set.

Table 9: Calculation method settings

Method of calculating X_{diff}	SPEED	**TE: DiffLeak = SPEED**
End-winding leakage reactance calculation method:	Richter	**TE: EndLeak = RICHTER**
Method of calculating deep-bar factors	Classical	**TE: DeepBar = Classical**
Component of (rotor side) *Carter* factor		**TE: qC_R = 1 (for semi-closed slots)**
Method for calculating iron losses	SPEED	**TE: WFeCalc: SPEED**

2. Numerical computation of machine performances

For a better understanding, all the values, which are necessary for the input into the program, are again presented in Fig. 3 to 5.

The calculated values for power factor (**P.F.**), torque (**TorqSh**), current densities (**Jrms**, **Jrotor**) etc., are located in design sheets. Beside the specification of a desired power (the program calculates then the associated slip) it is also possible to perform calculations for a given slip value. For this the parameter **CalcMode** (Figure1, Control Parameters) must be changed of **f/PowerSh** on **f/slip** and the appropriate slip (**Slip**) to be entered. Thus starting current / rated current ratios can be determined. The ratio pull-out torque / rated torque (**TBrkpu**) can be directly read! Are all values within the demanded range, the recalculation of the design with the values supplied by the program is to be performed.

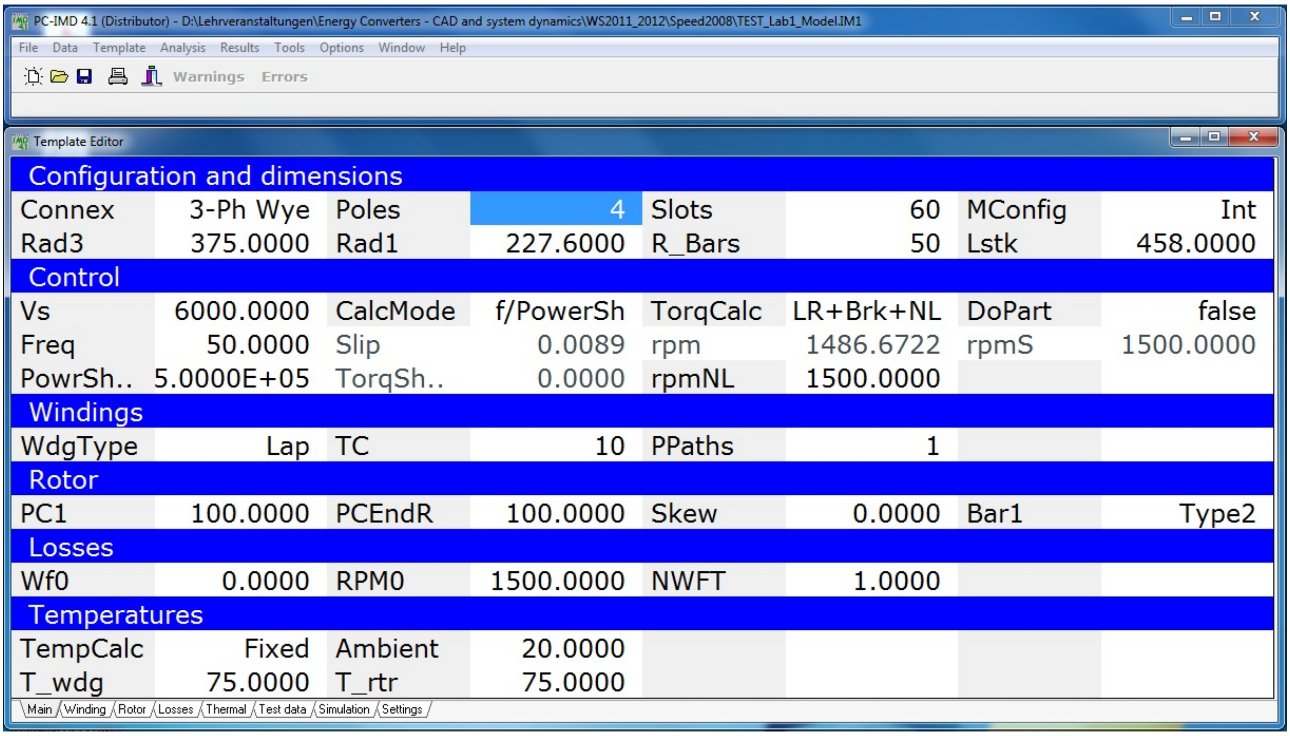


Fig. 3: Template Editor: Main specifications

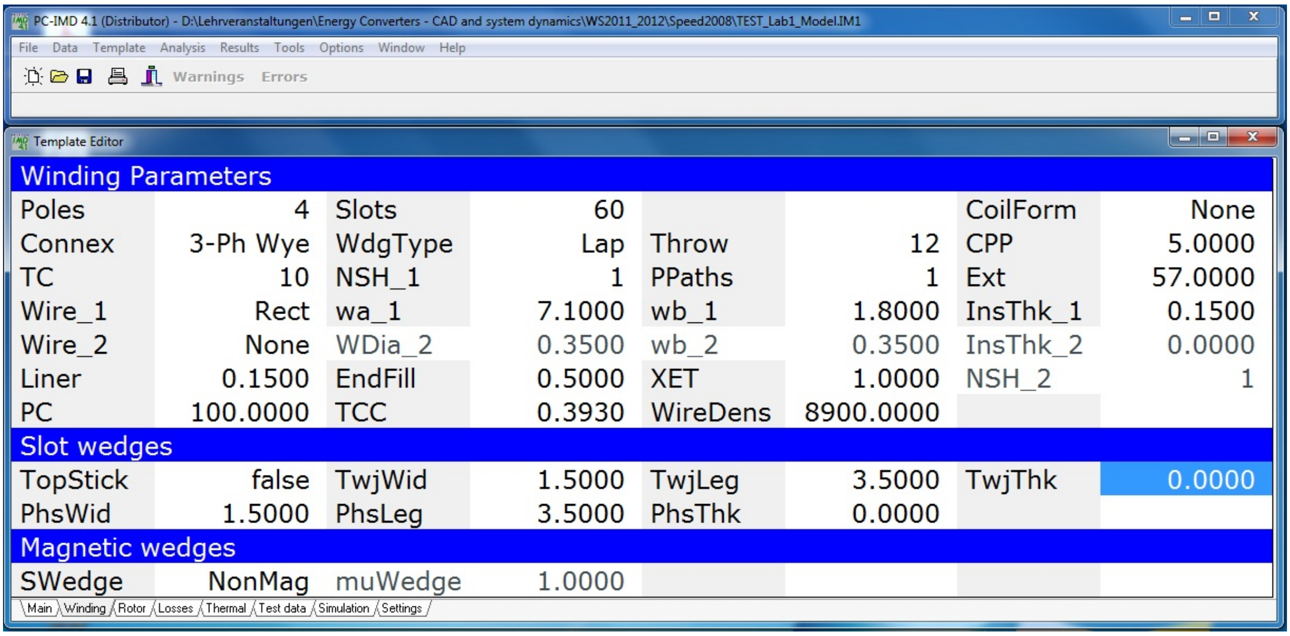


Fig. 4: Template Editor: Winding settings

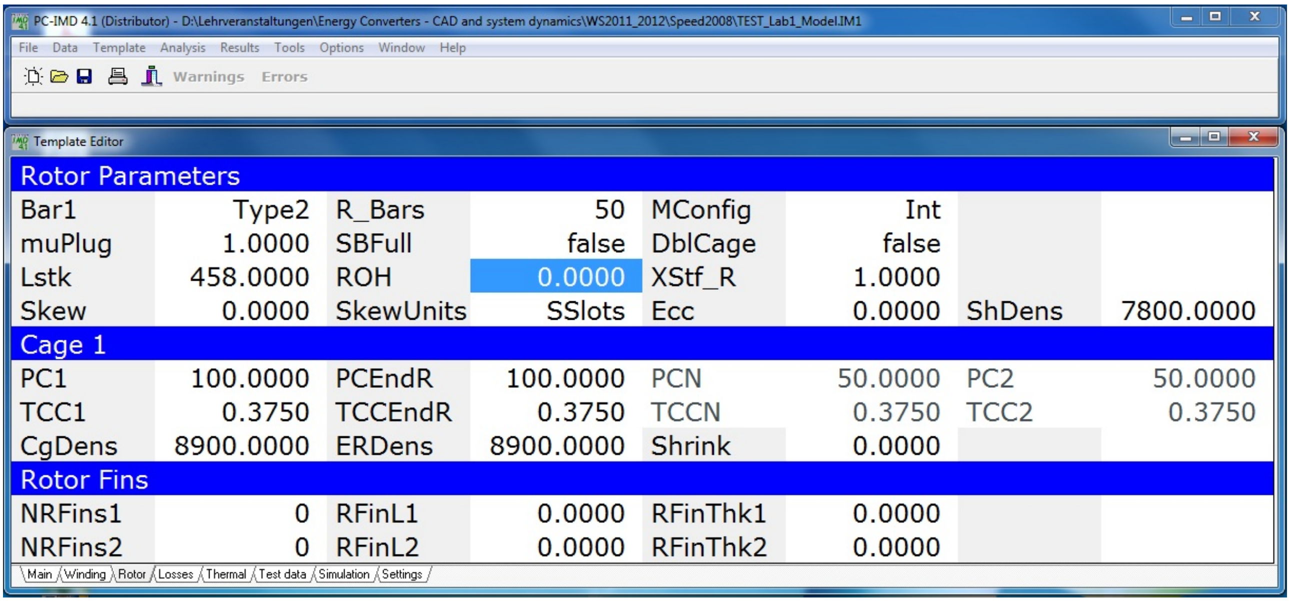


Fig. 5: Template editor: Rotor settings

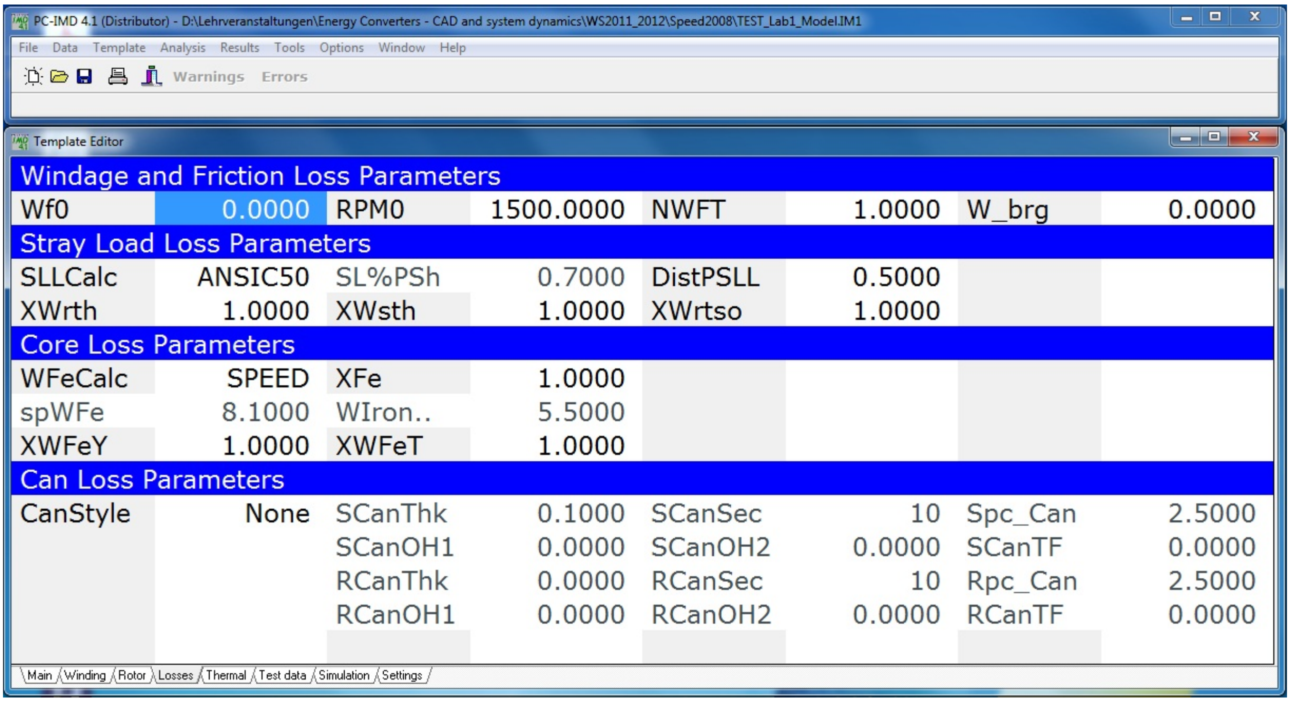


Fig. 6: Template editor: Loss calculation settings

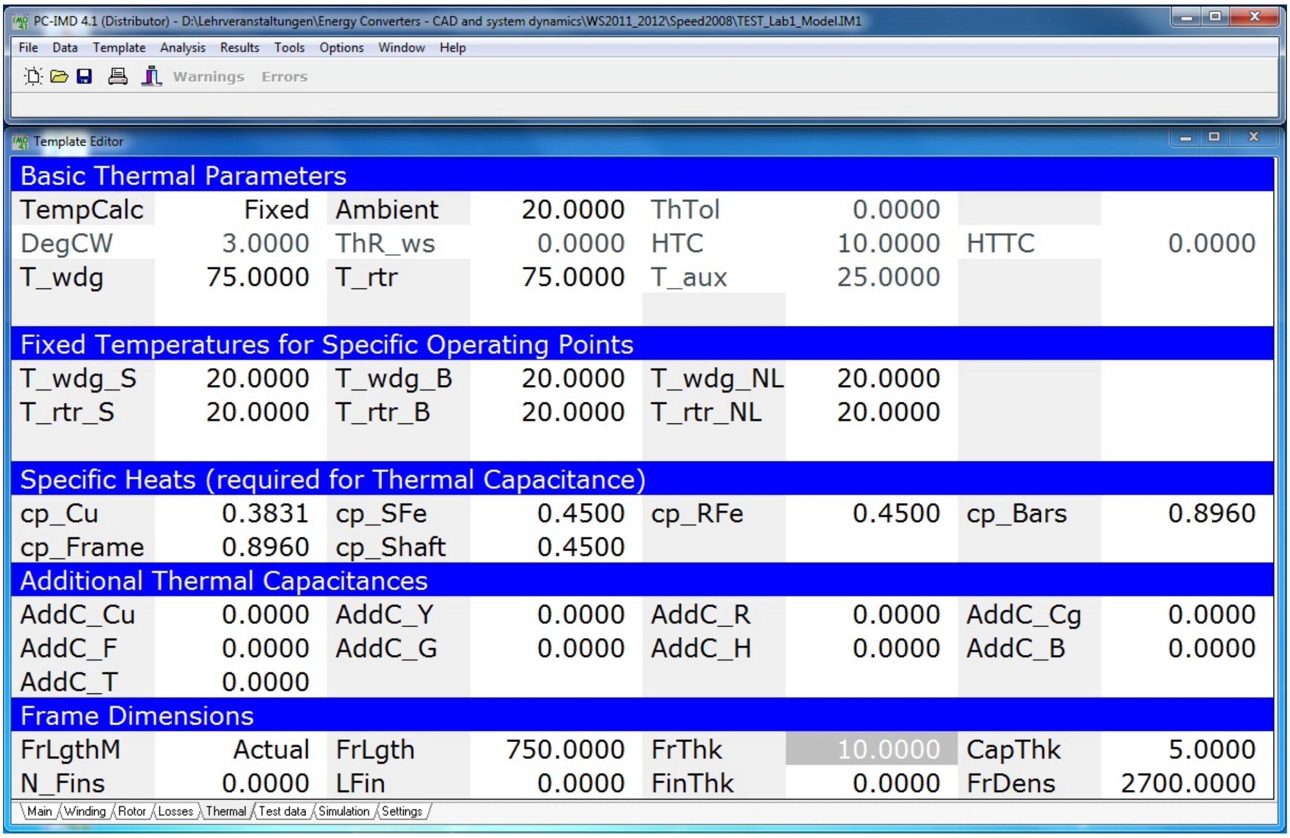


Fig. 7: Template editor: Thermal calculation settings

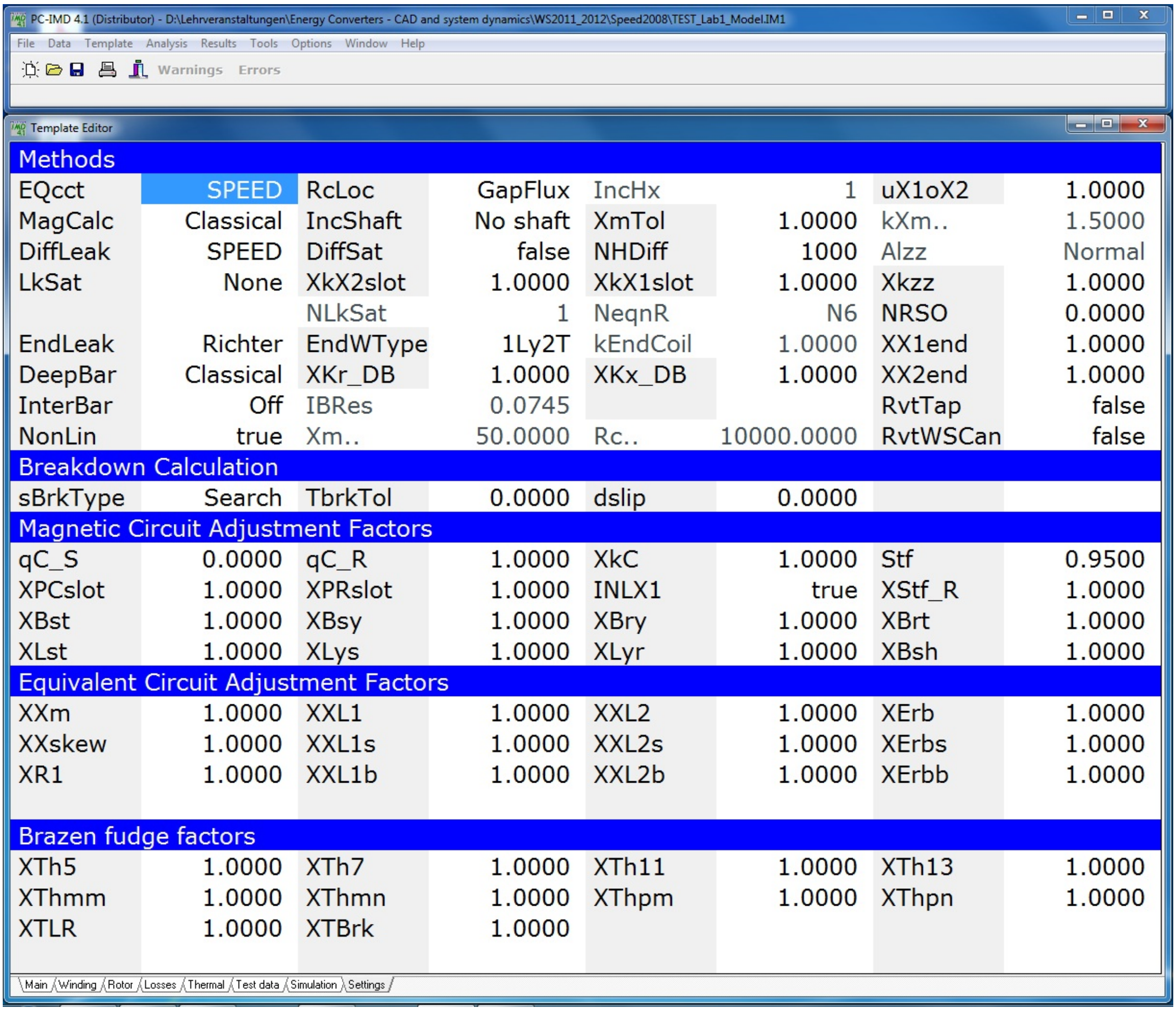
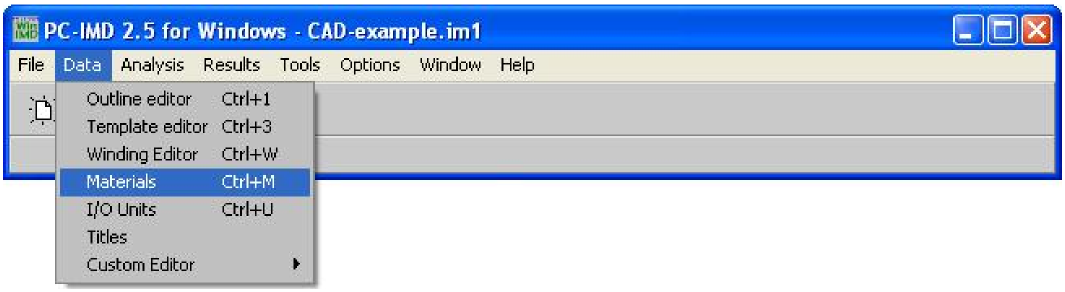
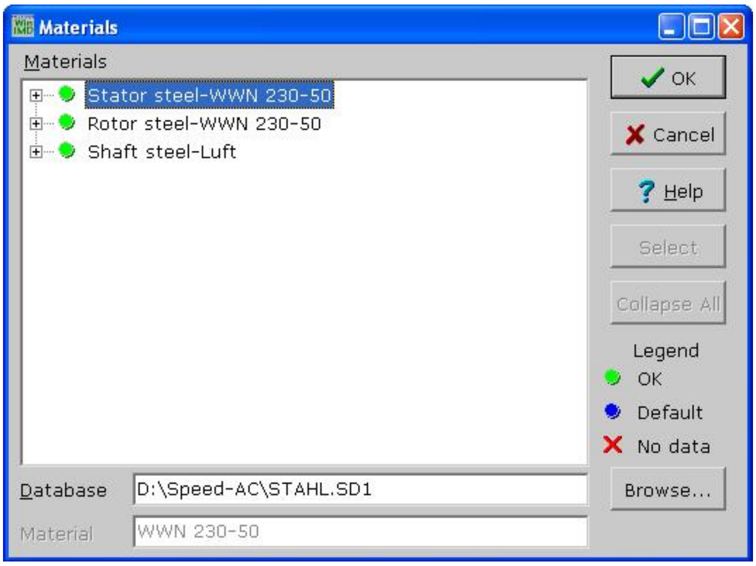


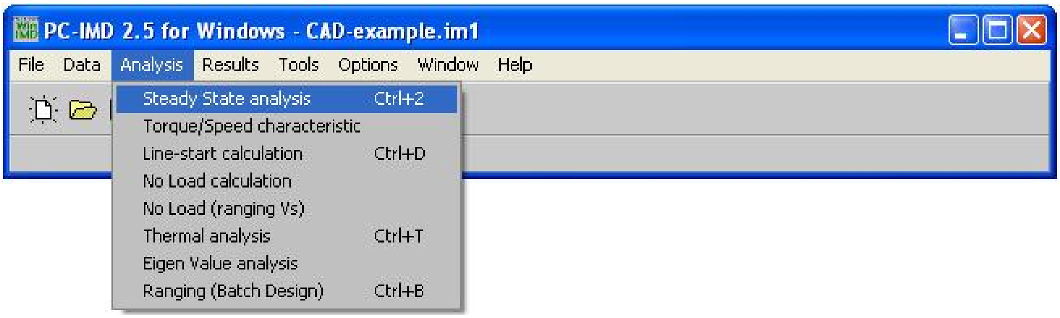
Fig. 8: Template editor: Calculation method settings

Make sure that the correct material curves are loaded:

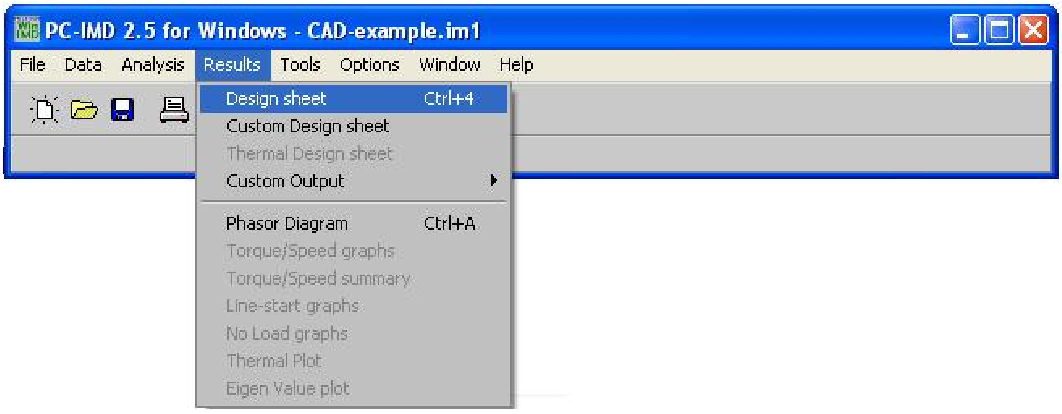




After all settings were made, start the calculation by clicking on **Steady State analysis**:



Finally see the calculation results in the **Design sheet**:



```
PC-IMD 4.1 (4.1.1.26) 26-Sep-2011 15:55:15
TU Darmstadt IEE

PC-IMD Design sheet

1 Dimensions : --------------------------------------------------------------

Slots              60          Poles               4          Lstk        458.0000 mm
StatorOD     750.0000 mm       RotorOD      455.2000 mm       Gap           1.4000 mm
StatorID     458.0000 mm       RotorID      200.0000 mm       MConfig          Int

STATOR..
Rad3         375.0000 mm       R1g          229.0000 mm
S-slot        PllSlot          ASlot        863.5539 mm^2     ASlotLL     839.0786 mm^2
SD_S          69.0000 mm       SWid          12.5000 mm       TGD_S     1.0000E-03 mm
STOH           0.0000 mm       SBWid         12.5000 mm       SYoke        77.0000 mm
NSDuct              8          WSDuct        10.0000 mm       LFeS        359.1000 mm
SWedge         NonMag          muWedge        1.0000

ROTOR..
Rad1         227.6000 mm       Rad0           0.0000 mm       RadSh       100.0000 mm
Bar1            Type2          R_Bars             50          DblCage        false
Skew           0.0000 SSlots   LB           458.0000 mm       BarExt        0.0000 mm
ARslot       208.7557 mm^2     Abar         200.0000 mm^2     Shrink        0.0000
muPlug         1.0000          SBFull          false          RYoke        84.0966 mm
Rotor slot dimensions..
BarDpth       40.0000 mm       BarWdth        5.0000 mm       SO_R          2.5000 mm
SetBack        3.5000 mm
Dbar         411.6966 mm

Rotor end-rings and fins..
ERType1        Type C
ERType2        Type C
ERLedge1       0.0000 mm       ERthk1        20.0000 mm       ERID1       368.1931 mm
ERLedge2       0.0000 mm       ERthk2        20.0000 mm       ERID2       368.1931 mm
ERArea1      800.0697 mm^2     ERArea2      800.0697 mm^2     EROD        448.2001 mm
NRDuct              8          WRDuct        10.0000 mm
ROH            0.0000 mm       LFeR         359.1000 mm

Shaft..
RadSh        100.0000 mm       RadSh2         4.8000 mm       RadSh3        3.6000 mm
AxExSh1        0.0000 mm       AxExSh2        0.0000 mm       AxExSh3       0.0000 mm

Stacking factors..
Stf            0.9500          XStf_R         1.0000

2 Winding Data : ------------------------------------------------------------

General
Connex       3-Ph Wye
PC           100.0000 %Cu      TCC            0.3930 %/°C     WireDens   8900.0000 kg/m³
SFill          0.2960          SFillHBL       0.4716          ACu         255.6000 mm^2
MaxSFg         0.2960          MaxSFn         0.4716          ASlotLL     839.0786 mm^2
ACL        69006.2284 mm^2     LCL          150.6686 mm       Liner         0.1500 mm
PCSlot         1.8401          XPCslot        1.0000
EndFill        0.5000          LaxPack      712.0051 mm       LAYERS        2.0000
Ax1md         54.0000 mDeg     Ax2md        114.0000 mDeg     Ax3md       174.0000 mDeg

Stator winding..
WdgType           Lap          T_wdg         75.0000 °C       RLL_Amb       1.1800 ohm
Throw              12          CPP            5.0000          TC                10
Tph          200.0000          PPaths              1          Tph1        181.9708
MLT         2186.8835 mm       XET            1.0000          Ext          57.0000 mm
Wire_1           Rect
```

```
wa_1          7.1000 mm
wb_1          1.8000 mm
NSH_1              1          EWG         40.3386
BWDia_1       4.0339 mm       EWDia        4.0339 mm
BWArea_1     12.7800 mm^2     ACond       12.7800 mm^2
InsThk_1      0.1500 mm
HBWDia_1      4.4482 mm

Winding factors..
kw1           0.9099          kw3         -0.3804          kw5           0.0000
kw7          -0.0878          kw9          0.2351          kw11         -0.1041
kw13         -0.0601          kw15         0.0000          kw17          0.0601
kw19          0.1041          kw21        -0.2351          kw23          0.0878
ks1           1.0000          kr_RS     7947.2112          zSlot             20

Rotor cage
CgDens     8900.0000 kg/m³    ERDens    8900.0000 kg/m³    SBFull         false
PC1         100.0000 %Cu      TCC1         0.3750 %/°C     RhoBar    2.0796E-08 ohm-m
PCEndR      100.0000 %Cu      TCCEndR      0.3750 %/°C     RhoEndR   2.0796E-08 ohm-m
Kring1        0.9619          Kring2       0.9619
PRSlot        4.1267          XPRslot      1.0000

3 Control Data : ------------------------------------------------------------

CalcMode   f/PowerSh
Freq         50.0000 Hz       PowrSh..  5.0000E+05 W
rpmS       1500.0000 rpm      rpm       1486.6834 rpm      Slip          0.0089 p.u.
Vs         6000.0000 V        Drive      AC_Volts

4 Magnetic design : ---------------------------------------------------------

SSteel    WWN 230-50
RSteel    WWN 230-50
ShSteel         Luft
MagCalc    Classical          XBst         1.0000          XBrt          1.0000
XBsy          1.0000          XBry         1.0000          XBsh          1.0000
                                                           IncShaft    No shaft
PPitch      359.7124 mm       Ag           0.0000 mm^2     Lge           2.7881 mm
qC_S          0.0000          qC_R         1.0000          XkC           1.0000
kC_s          1.5018          kC_r         1.0372          kC            1.9915
kC_sd         1.1307          kC_rd        1.1307
muPlug        1.0000          PCplug       1.4000
Bstpk         2.0330 T        ATst       733.9806 A        MMFst         0.4328 p.u.
Brtpk         1.3280 T        Atrt        35.2505 A        MMFrt         0.0208 p.u.
Bsypk         1.4496 T        ATsy        95.8747 A        MMFsy         0.0565 p.u.
Brypk         1.3273 T        ATry        28.1934 A        MMFry         0.0166 p.u.
Bshpk         0.0000 T        ATsh         0.0000 A        MMFsh         0.0000 p.u.
Bg1L          0.7643 T        ATgap     1695.8217 A        kXm           1.5268
Bgm           0.4866 T        Bgpk         0.7643 T        Phi1L        80.1649 mWb

5 Equivalent circuit parameters : -------------------------------------------

R1            0.7175 ohm      X1           6.6658 ohm      X1unsat       6.6658 ohm
R2            0.5418 ohm      X2           6.4149 ohm      X2unsat       6.4149 ohm
Rc         9207.5856 ohm      Xm0        234.8003 ohm      Xm          158.3289 ohm
Rbar          0.3791 ohm      REndRing     0.1627 ohm      Erb           0.0000 V
R_rotor   6.8174E-05 ohm      X_rotor  8.0719E-04 ohm      XErb          1.0000
EQcct          SPEED          RcLoc       GapFlux
DeepBar    Classical          K_r          1.0016          K_x           0.9996
                              XKr_DB       1.0000          XKx_DB        1.0000
EndLeak      Richter          CoilFill     1.0000          kEndCoil      1.0000
                              XX1end       1.0000          XX2end        1.0000
DiffLeak       SPEED          NHDiff         1000          DiffSat        false
LkSat           None          kXL1         1.0000          kXL2          1.0000
```

```
kzz            1.0000        kX1slot        1.0000        kX2slot        1.0000
Xkzz           1.0000        XkX1slot       1.0000        XkX2slot       1.0000
XXm            1.0000        XXL1           1.0000        XXL2           1.0000

Unsaturated reactance components..
X1slot         1.8672 ohm    X1end          4.5180 ohm    X1diff         0.2806 ohm
X2slot         4.8918 ohm    X2end          1.2782 ohm    X2diff         0.2448 ohm

L-circuit parameters..
alpha_TL       1.0405        uX1oX2         1.0000        X1oX2          1.0391
XL_L          13.8811 ohm    Rc_L        9968.8143 ohm
R2_L           0.5866 ohm    Xm_L         164.7438 ohm

6 Performance : ------------------------------------------------------------

OpMode      Motoring
Vt         6000.0000 V       rpm        1486.6834 rpm    Slip           0.0089 p.u.
Pshaft    4.9997E+05 W       PElec     5.2140E+05 W      Tshaft      3211.4200 Nm
PshaftHP    670.4711 h.p.    P.F.          0.8552        Effcy         95.8893 %
                             WTotal    21435.0875 W      Eff_X_PF      82.0084 %
Currents..
Iph1          58.6643 A rms  IL1          58.6643 A rms  I2            52.8085 A
Imc           20.4703 A      IMag         20.4673 A      Ic             0.3519 A

Equivalent circuit voltages..
E1         3240.5650 V       VR1          42.0943 V      VX1          391.0422 V
ER2        3194.1983 V       VR2          28.6113 V      VX2          338.7613 V

Losses and related parameters..
WCuS       7408.3039 W       WCuR       4532.7666 W      WIron       3421.5033 W
SLLCalc      ANSIC50         WSLL       6072.5137 W      Wwf            0.0000 W
Jrms           4.5903 A/mm^2
JBar1          5.7658 A/mm^2 J_ER          5.7499 A/mm^2 JRotor         5.7329 A/mm^2

Other performance parameters..
PGap      5.1058E+05 W       EMTorque   3250.4251 Nm

Locked-rotor..
TLR        3219.1352 Nm      TLRpu         1.0024        sLR            1.0000 p.u.
ILR         343.5242 A       ILRpu         5.8558        PFLR           0.2002
PLR       7.1454E+05 W
pTWdg          3.6533 C/sec  pTBar         9.5613 C/sec
C_Cu          57.1755 kJ/C   C_cage       52.8862 kJ/C
T_wdg_S       20.0000 °C     T_rtr_S      20.0000 °C
XXL1s          1.0000        XXL2s         1.0000        XErbs          1.0000

Breakdown..
TBrk       7958.7126 Nm      TBrkpu        2.4783        sBrk           0.0363 p.u.
IBrk        187.9838 A       IBrkpu        3.2044        PFBrk          0.6809
rpmBrk     1445.6086 rpm     PBrk      1.3302E+06 W
T_wdg_B       20.0000 °C     T_rtr_B      20.0000 °C     sBrkType       Search
XXL1b          1.0000        XXL2b         1.0000        XErbb          1.0000

No-load..
INL           22.0592 A      NLTorque      0.0000 Nm     NLPF           0.0193
INLpu          0.3760        TNLpu         0.0000        NLrpm       1500.0000 rpm
T_wdg_NL      20.0000 °C     T_rtr_NL     20.0000 °C     rpmNL       1500.0000 rpm
PNL        4418.0537 W       XLL_NL      314.0145 ohm    INLX1            true

Test data..
Wrated         0.0000 W      Irated        0.0000 A
V_Test     6000.0000 V       I_Test        0.0000 A      P_Test         0.0000 W
s_Test         0.0000        T1_Test      20.0000 °C     T2_Test       20.0000 °C
```

```
7 Core losses, Harmonic losses, and Stray Load Losses : ----------------------

WFe0S         3.5086 W/kg   WFe0R         3.5086 W/kg   WFe0Sh        3.6719 W/kg
WFeS       3414.1815 W      WFeSe       884.0935 W      WFeSh      2530.0879 W
Wst        1702.4924 W      Wste        457.9210 W      Wsth       1244.5715 W
Wsy        1711.6891 W      Wsye        426.1726 W      Wsyh       1285.5165 W
WstWkg        6.0128 W/kg   WsyWkg        3.3026 W/kg
WFeR          7.3218 W      WFeRe         0.0209 W      WFeRh         7.3009 W
Wrt           2.7773 W      Wrte          0.0079 W      Wrth          2.7694 W
Wry           4.5445 W      Wrye          0.0130 W      Wryh          4.5315 W
WrtWkg        0.0190 W/kg   WryWkg        0.0190 W/kg
WFeCalc        SPEED        XFe           1.0000        Bd_slot       0.5951 T

8 Thermal data : -------------------------------------------------------------

TempCalc       Fixed        HeatFlux      7.7389 kW/m²  TempRise     55.0000 °C
Ambient      20.0000 °C
T_wdg        75.0000 °C     T_rtr        75.0000 °C

9 Miscellaneous parameters : -------------------------------------------------

Wt_Cu       149.2443 kg     Wt_Fe      1092.8759 kg     Wt_Tot     1301.1450 kg
WtFeS       717.0246 kg     WtFeR       375.8514 kg
WtFesy      518.2904 kg     WtFest      198.7318 kg     WtTri        84.4109 kg
Wt_Al        59.0248 kg     WtAl_RB      40.7620 kg     WtAl_ER      18.2628 kg
WtShaft     183.7832 kg
RotJ         13.9842 kg-m²  JL            0.0000 p.u.   JFan          0.0000 p.u.
C_cage       52.8862 kJ/C   C_main       57.1755 kJ/C
WtFrame      54.0323 kg     WtCap         2.8416 kg
Ecc           0.0000        UMP      2.0010E-13 kg
FrThk        10.0000 mm     LFrame      750.0000 mm     CapThk        5.0000 mm
FrLgthM       Actual        FrLgth      750.0000 mm
TRV       43086.1054 Nm/m3  T/Wt          2.4681 Nm/kg  P/Wt        384.2541 W/kg
Wf0           0.0000 W      RPM0       1500.0000 rpm    NWFT          1.0000
CanStyle        None
NumHoles           4        PCDia       286.5000 mm     HoleDia      30.0000 mm
RTC_OC        2.0256 sec    RTC_SC        0.1083 sec


End of Design sheet-----------------------------------------------------------
```

3. Speed – exercise

1) The number of turns per coil will be decreased from 10 to 9. Decreasing the number of turns per coil allows increasing the cross-section of cupper (h_L from 1.8 mm to 2 mm). Calculate the new motor impedances, the starting current and the starting torque! Do the motor impedances change? How do starting torque and current vary in comparison to the initial data?

2) How do the air-gap induction, the primary current at rated slip and the electric loading change?

References:

[1] A.Binder, *Energy Converters: CAD and System Dynamics*, Text book – TU Darmstadt, 2009
[2] A.Binder, *CAD and System Dynamics of Electrical Machines*, Text book – TU Darmstadt, 2006 ÷ 2008
[3] A.Binder, *Motor Development for Electric Drive Systems,* Text book – TU Darmstadt, 2006 ÷ 2009
[4] A.Binder, *CAD and System Dynamics of Electrical Machines,* Tutorial for Exercise– TU Darmstadt, 2006- 2008
[5] A.Binder, *Energy Converters: CAD and System Dynamics,* Tutorial for Exercise – TU Darmstadt, 2009
[6] ****, *User's Manual for PC-IMD 2.5*, University of Glasgow, 1998
[7] A.Binder, M. Aoulkadi, *CAD and System Dynamics of Electrical Machines: Design of an Asynchronous Machine*, Tutorial for Exercise, 2006
[8] O.Magdun, A.Binder, *Energy Converters - Asynchronous Machine*, Guide for Computer Aided Design, 2009

Abbreviations PC-IMD

	Symbol		Unit	Denotation	
Dimensional	BarDpth	h_r	mm	Rotorbar depth	Leiterhöhe des Rotorstabes
	BarWdth	b_r	mm	Rotorbar width	Leiterbreite des Rotorstabes
	ERLedge		mm	Additional endring length	Zusätzliche radiale Endringlänge
	Erthk		mm	Endring thickness	Endringdicke (1=linker, 2=rechter)
	Gap	δ	mm	Airgap length	Luftspaltweite
	Lstk	l	mm	Rotor and Stator stack length	Blechpaketlänge
	Poles	p	-	Number of Poles	Polzahl
	RadSh		mm	Shaft radius	Radius der Welle
	R-Bars	Q_r	-	Number of rotor bars or slots	Rotornutzahl
	SD-S	h_S	mm	Stator slot depth	Statornuttiefe
	SetBack		mm	Set-Back	Rotorstreusteghöhe
	Skew	k_{sq}	-	Rotor skew	Schrägung des Rotors um x – Nuten
	Slots	Q_s	-	Number of stator slots	Statornutzahl
	SO-R		mm	Rotor slot opening	Nutöffnung Rotor
	SO-S		mm	Stator slot opening	Nutöffnung Stator
	S-slot		-	Shape of Stator slot bottom	Statornutform
	Stf	k_{Fe}	-	Stacking factor	Stapelfaktor
	TGD-R		mm	Rotor tang depth	Streusteghöhe Rotor
	TGD-S		mm	Stator tang depth	Streusteghöhe Stator
	TW-S	b_{ds}	mm	Stator tooth width	Statorzahnbreite
Winding	Connex		-	Winding connection	Anschlussart
	Coils/P	q	-	Number of coils per pole	Nuten je Pol und Strang
	Ext		mm	Winding extension at each end	Gerader Leiter außerhalb Eisen
	LAYERS		-	Number of layers	Anzahl der Spulenlagen pro Nut
	Liner		mm	Thickness of stator slot-liner	Dicke der Nutauskleidung
	NSH	b	-	No. of strands in hand	Anzahl der parallelen Teilleiter
	PPaths	a	-	No. of parallel paths	Anzahl der parallelen Zweige
	TC	N_c	-	Turns per coil	Spulenwindungszahl
	Throw	y	-	Throw	Spulenweite
	WdgTemp	ϑ	°C	Winding temperature	Wicklungstemperatur
	WdgType		-	Type of winding	Wicklungsart
	Wire		mm	Wire size or gauge	Leiterdurchmesser
Control	Freq	f	Hz	Fundamental line frequency	Speisefrequenz
	rpm	n	min^{-1}	Actual shaft speed	Drehzahl
	rpmS	n_S	min^{-1}	Synchronous speed	Synchrondrehzahl
	Slip	s	-	Slip	Schlupf
	Vs	U	V	RMS AC line voltage	Spannung

Magnetic	Bg1L	$B_{\delta 1}$	T	Peak fundamental flux-density	Maximalwert Luftspaltflussdichte
	Bgm	$B_{\delta av}$	T	Mean airgap flux-density	Mittlere Luftspalt Flussdichte
	Bstpk	B_{ds}	T	Peak Stator tooth flux-density	Statorzahn Flussdichte
	Brtpk	B_{dr}	T	Peak rotor tooth flux-density	Rotorzahn Flussdichte
	Bsypk	B_{ys}	T	Peak stator yoke flux-density	Statorrücken Flussdichte
	Brypk	B_{yr}	T	Peak rotor yoke flux-density	Rotorrücken Flussdichte
	Bshpk	B_{s}	T	Peak shaft flux-density	Rotorwelle Flussdichte
	KC_s	k_{Cs}	-	Carter coefficient for stator slot	CARTER-Faktor
Equivalent	R1	R_{s}	Ω	Primary resistance/phase	Statorwiderstand
	R2	R_{r}	Ω	Secondary resistance/phase	Rotorwiderstand
	X1	$X_{\sigma s}$	Ω	Primary stray reactance	Statorstreureaktanz
	X2	$X_{\sigma r}$	Ω	Secondary stray reactance	Rotorstreureaktanz
	Xm	X_{hges}	Ω	Saturated magnetising reactance	Hauptreaktanz (gesättigt)
	Xm0	X_{hung}	Ω	Unsaturated magnetising	Hauptreaktanz (ungesättigt)
Performance	Effcy	η	%	Efficiency	Wirkungsgrad
	IL1	I	A	RMS line current	Statorstrom
	I2	I	A	Rotor current	Rotorstrom
	Imag	I_{m}	A	Magnetising current	Magnetisierungsstrom
	Jrms	J	A/mm^2	RMS current-density main wind.	Statorstromdichte
	Jbar1	J	A/mm^2	RMS current-density rotor cage	Rotorstabstromdichte
	P.F.	$\cos\varphi$	-	Power factor	Leistungsfaktor cosφ
	Pelec	P_{e}	W	Mean electrical power	Elektrische Leistung
	PowerSh	P_{m}	W	Shaft power	Mech. Leistung
	TbrkR	m_{b}	-	Ratio Breakdown/rated Torque	Verhältnis Kipp-/Nennmoment
	WcuR	P_{Cur}	W	Rotor copper losses	Kupferverluste Rotor
	WcuS	P_{Cus}	W	Stator copper losses	Kupferverluste Stator
	Wiron	P_{Fe}	W	Iron (Core) loss	Eisenverluste
	Wwf	P_{R}	W	Windage and friction loss	Ventilations- & Reibungsverluste
Core Loss	WFeS	P_{Fes}	W	Stator Iron (Core) loss	Eisenverluste Stator
	WFeR	P_{Fer}	W	Rotor Iron (Core) loss	Eisenverluste Rotor
	WstWkg		W/kg	Specific stator teeth core losses	Spezifische Stator-Zahn Eisenverluste
	WsyWkg		W/kg	Specific stator yoke core losses	Spezifische Stator-Joch Eisenverluste
Miscellaneous	RPM0	n_{0}	min^{-1}	Shaft speed at no load	Leerlaufdrehzahl
	Wt_Al	m_{r}	kg	Weight of rotor cage	Gewicht Rotorkäfig
	Wt_Cu	m_{s}	kg	Weight of copper in stator wind.	Wicklungsgewicht Stator
	Wt_Fe	m	kg	Weight of iron stator / rotor lams	Gesamteisengewicht Stator/Rotor
	Wt_Tot	m	kg	Total active weight	Gesamtgewicht (Al+Cu+Fe)
	Wf0	P_{R}	W	Windage and friction loss	Ventilations- & Reibungsverluste
Thermal	Ambient	ϑ_{a}	°C	Ambient	Umgebungstemperatur
	RoTemp	ϑ_{r}	°C	Rotor cage temperature	Rotortemperatur
	TempCalc			Temperature calculating method	Temperatur-Berechnungsmethode
	WdgTemp	ϑ_{Wi}	°C	Stator winding temperature	Wicklungstemperatur Stator
	Rad1		mm	Rotor surface Radius	Außenradius des Läufers
	Rad3		mm	Stator outer radius	Außenradius Stator
	R-Cage		-	Rotor-cage	Nutform des Rotors